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UNIDIRECTIONAL CORE-SHELL HYBRIDS FOR CONCRETE REINFORCEMENT - A PRELIMINARY STUDY

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By L.J. Malvar

Fiber-reinforced plastic (FRP) bars are currently being used to replace steel bars as concrete reinforcement. For non-prestressed applications, these FRP bars exhibit a relatively low modulus of elasticity and a lack of ductility. This report shows that two-fiber hybrid composites can be optimized to obtain a rebar with a modulus of elasticity equal to steel, as well as a pseudo-plastic behavior. This pseudo-plastic behavior corresponds to the gradual transfer of the load from the low-elongation fibers being ruptured to the high-elongation fibers. Hardening characteristics can be obtained which allow for a gradual fiber rupture. By placing the low-elongation fibers in the center of the rebar, and by winding the high-elongation fibers as a helical shell around this core, higher rebar strains to failure can be obtained. The ratio of the rebar failure strain to the rebar yield strain can be enhanced by increasing the shell fiber's angle with respect to the rebar longitudinal axis.
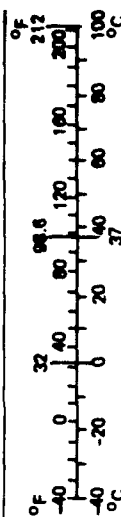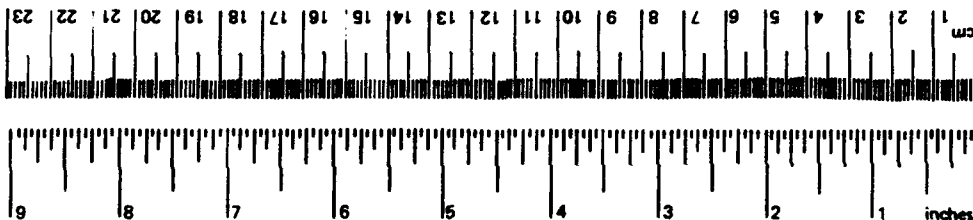
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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

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PREFACE

On 1 October 1993, the Naval Civil Engineering Laboratory (NCEL) was consolidated with five other Naval Facilities Engineering Command (NAVFAC) components into the Naval Facilities Engineering Service Center (NFESC). Due to publishing timeframes, this document may have references to NCEL instead of NFESC.

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CONTENTS

BACKGROUND

Extensive and costly condition assessment, repair, and rehabilitation programs are underway to extend the service life of Navy waterfront structures. The main cause of deterioration is concrete cracking and corrosion of steel reinforcement exposed to the marine environment and aggressive agents such as deicing salts for bridges and pavements. To prevent this corrosion, galvanized and epoxy-coated steel reinforcing bars are currently being used and investigated with mixed results (Ref 1). A more recent alternative is the use of fiber-reinforced plastic (FRP) bars which have excellent corrosion resistance properties and some mechanical properties comparable to steel (Refs 2 through 13).

However, FRP rebar has important shortcomings when used in non-prestressed applications (Ref 4). The first FRP rebar shortcoming is its low modulus of elasticity, which is around 1/4 that of steel, as shown in Figure 1. Although in prestressing applications this low modulus is actually beneficial (it reduces prestressing losses), for reinforcing applications it results in excessive deflections and increased cracking. In the case of beams, the low stiffness raises the neutral axis and further reduces the depth of the concrete compression zone (Ref 14). This reduces the contribution of the concrete itself to the load carrying capacity, and explains why high strength concrete is usually suggested with FRP rebar.

A second FRP rebar shortcoming is its lack of ductility. Stress-strain relationships are linear almost up to failure, which typically occurs at less than 3.5 percent strain. This is in contrast with steel rebar which routinely exhibits elongations at rupture in excess of 10 percent (see Figure 1).

Finally, a third FRP rebar shortcoming is the potential strength loss due to fiber degradation when embedded in concrete (Refs 12, 15, 16, and 17).

OBJECTIVES

With regard to the first and second shortcomings, it is proposed that an ideal FRP rebar be analytically investigated which would exhibit a stress-strain curve reminiscent of steel. The proposed rebar should be capable of exhibiting high initial stiffness, a pseudo-plastic stage, and high strain to failure. Particular attention should be paid to hybrid composites which include various fibers embedded in a common matrix. With regard to the third shortcoming, an overview of the durability of fibers and FRP rebars in strong basic environments (i.e., in concrete) is presented.

MATERIALS

Current FRP rebar composites use three types of fibers: carbon, aramid, and glass (Ref 18). Glass fibers are the least expensive and the most commonly used. E-glass fibers are the cheapest and most common (Refs 19 and 20), but S-glass fibers have more desirable properties (Refs 5, 18, and 21) as indicated in Table 1. All the FRP rebars shown in Figure 1 use E-glass fibers. Aramid fibers have slightly higher tensile moduli E (between 12 and 27 Msi,

1

with 1 Msi = 10^3 ksi = 10^6 psi) and similar tensile elongations (between 2 and 4 percent) (Ref 22). Carbon fibers, however, offer a wide variety of moduli from 25 to 120 Msi. Mesophase pitch fibers have values of E between 100 and 120 Msi (Refs 23 and 24).

With regard to environmental interaction, carbon fibers are not affected by moisture, atmosphere, solvents, bases, and weak acids (Ref 25). Glass fibers, however, are chemically vulnerable to many acids and bases and will deteriorate if in direct contact with concrete. Para-aramid fibers (such as Kevlar) are affected by strong acids and bases, but are fairly resistant to most other solvents and chemicals (Refs 22 and 26), as well as seawater (Refs 27 and 28). In composites, it is generally expected that the matrix will provide the needed chemical protection for the fibers. Carbon fibers have the potential to withstand direct interaction with concrete for long periods of time (Refs 29 and 30) and have been used extensively in Japan for reinforcing bars (Refs 31 and 32).

The long term static strength has been reported to be 70 percent of the short term static strength for E-glass composites (Refs 6 and 33). For carbon composites, this ratio is similar. For Kevlar fibers and a 100-year static loading, this ratio is around 60 percent (Refs 27 and 33).

With respect to the matrix, epoxies and polyester have been used for their fiber protection properties. Within the polyesters, vinyl ester resins are resistant to a wide range of acids (sulfuric, hydrochloric, hydrofluoric, phosphoric, nitric) as well as to chloride salts and chlorine (Refs 18 and 26), making them ideal for marine environments. For use in concrete, bisphenol A (BPA) fumarates have shown the best resistance to strong basic solutions (Ref 18).

However, recent tests on glass FRP rebar under tensions as low as 30 percent of ultimate have shown that standard low elongation matrices will exhibit microcracking which in turn will allow direct contact between fibers and concrete (Ref 17). This problem can be addressed by using resins with higher toughness and ultimate strains (Ref 17). Although currently used resins exhibit elongations at failure up to 4 percent, values of 10 percent or more can be obtained (Refs 26 and 34). Besides microcracking, diffusion of hydroxyl ions through the matrix will also result in deterioration of the fibers and loss of the rebar (Refs 15 and 16).

With respect to fiber content, total contents of up to 68 percent by volume (80 percent by weight for glass fibers) can be routinely obtained (Ref 26) for uniaxial composites. Contents from 60 percent (Ref 35) to 80 percent (Ref 19) by weight (i.e., 45 to 68 percent by volume) have been reported.

HYBRID COMPOSITES

By using a two-fiber hybrid composite employing carbon, aramid, or glass fibers, the properties of both fibers can be optimized to produce desired composite properties (Refs 36 and 37). For example, a composite with 27.5 percent by volume of E-glass fibers and 27.5 percent by volume of P-100 carbon fibers (total 55 percent of fibers) would have the following modulus, E_c, using a rule of mixtures:

$$E_c = E_{gf}V_{gf} + E_{cf}V_{cf} + E_mV_m = 30.6 \text{ Msi}$$

where

$$E_{gf} = 10.5 \text{ Msi} = \text{modulus of glass fibers}$$

$$E_{cf} = 110 \text{ Msi} = \text{modulus of carbon fibers}$$

2

$$E_m \;=\; 0.52 \text{ Msi} \;=\; \text{modulus of neat resin (matrix)}$$

$$V_{gf} \;=\; 0.275 \;=\; \text{relative volume of glass fibers}$$

$$V_{cf} \;=\; 0.275 \;=\; \text{relative volume of carbon fibers}$$

$$V_m \;=\; 0.450 \;=\; \text{relative volume of matrix}$$

This is a good approximation for the modulus of a unidirectional composite (Ref 18 p. 178, and Ref 38). The composite then has a modulus of elasticity very similar to that of steel, which is 29 Msi. At a strain of $\epsilon_{uc} = 0.0032$, however, the carbon fibers will fracture. Just prior to fracture the average stress in the composite is (Ref 39):

$$\sigma_c \;=\; \sigma_{uc}V_{cf} + (E_{gf}V_{gf} + E_mV_m)\,\epsilon_{uc} \;=\; 106 \text{ ksi}$$

where σ_{uc} is the ultimate strength of the carbon fibers. From then on, the resistance will be provided by the glass fibers and the matrix, assuming that the matrix did not fracture. Upon rupture of the glass fibers, at a strain of $\epsilon_{ug} = 4.8$ percent, the composite's ultimate stress is:

$$\sigma_c \;=\; \sigma_{ug}V_{gf} + E_mV_m\epsilon_{ug} \;=\; 149 \text{ ksi}$$

It is observed that, after fracture of the carbon fibers, the composite still has not reached its maximum resistance. This behavior is indicated in Figure 2. The desired monotonic stress-strain behavior of the proposed hybrid composite rebar after rupture of the carbon fibers is indicated by a straight line, representing a smooth transition which resembles yielding of a steel bar. Extant studies on uniaxial hybrid composites have shown that this pseudo-yielding can be observed experimentally (Refs 37 and 40). Concrete reinforcements using carbon/aramid and carbon/glass hybrids are already in commercial use (Ref 40), with ultimate strains up to 3.5 percent or initial stiffnesses up to 20 Msi.

Actual hybrid stress-strain behavior does present some differences from the previous analysis:

1. The strain to failure of the low-elongation fibers, in this case the carbon fibers, increases slightly (hybrid effect).

2. The strain to failure of the high-elongation fibers is somewhat reduced.

3. A smooth pseudo-yielding is only obtained when the transfer of load between broken carbon fibers and glass fibers is effective. This occurs when the fiber tows are intermingled, or when the layers of the various fiber composites are well bonded (i.e., this is highly dependent on the matrix properties and the fiber/matrix interface). For unbonded layers, the resulting behavior is just the superposition of each layer's response (Ref 41).

It should be noted that the ultimate strain of E-glass composites is often limited to values around 2.3 percent (Table 2), although values of 2.8 percent (Ref 40) and 3.4 percent (Ref 19) can be obtained. In the example, it is assumed that the monofilament strain of 4.8 percent can be attained.

3

DUCTILITY

Current design guidelines for FRP rebar reinforced structures are only provided by some researchers and manufacturers. Often a working stress design approach is recommended, with a limit on the allowable FRP rebar stress of 30 ksi (Refs 28, 35, and 42) (i.e., about 30 percent of the ultimate stress). This limit provides for problems such as long term strength, which can be as low as 60 percent of the short term strength.

The safety provided by limiting the working stress can be greatly enhanced by the presence of ductility or pseudo-ductility, a measure of which is the ductility ratio (i.e., the ratio of ultimate strain to yield strain). At the structure level, if the yield stress is exceeded at some locations, ductile materials will allow for the formation of plastic hinges that will redistribute the loads and prevent collapse (Ref 43). For a hybrid material, reaching the pseudo-plastic range would mean that some of the material has failed, however, this material failure would not induce a catastrophic structural failure. Since hardening can be included during the pseudo-plastic range, the structure will still be stable even after enough plastic hinges have appeared to form a mechanism.

Upon reaching a stress level in the pseudo-plastic range, the new loading-unloading modulus would be significantly lower than the initial modulus of elasticity, in contrast with metallic materials. This, however, can be advantageous, since it would allow for the detection of damaged bars.

In seismic areas, ductility is necessary to ensure large rotations and displacements, as well as energy dissipation, without collapse. Hybrid materials would allow for large deformations, force redistribution, and some energy dissipation without collapse.

UNIDIRECTIONAL CYLINDRICAL CORE-SHELL HYBRIDS

It was shown earlier that tensile moduli practically equal to that of steel can be obtained in hybrids by using high-modulus pitch carbon fibers. The overall ductility was, however, still limited to less than 5 percent (assuming a ductile matrix). In order to increase this ductility, it is proposed that carbon and glass fibers be separated, with the carbon fibers located in the center (core) of the bar, and the glass fibers placed as a shell around this core. The carbon fibers would remain oriented along the bar axis. The glass fibers would be wound around the core with a given pitch dependent on the ultimate elongation desired for the composite. This would produce a geometrical approach to achieving higher strains to failure and higher ductility ratios.

Although carbon fibers are more resistant than glass fibers to alkaline environments (Refs 29, 44, and 45), placing them in the core will provide them with additional protection since the design assumes that they will carry most of the load during most of the structure's life. The glass fibers have greater toughness and impact resistance (Ref 21) and would soften the stress concentrations on the carbon fibers due to concrete cracking. On the other hand, given the higher stiffness of the carbon fibers, the matrix will be subjected to low strains preventing any matrix cracking which would expose the glass fibers. It should be noted that the shell itself can be composed of carbon fibers, although this would limit the ultimate bar strain.

Only if the pseudo-yield of the composite is reached (i.e., if the carbon core is ruptured), will the shell's fibers carry the load. In this case, the bar design will have prevented catastrophic failure, and redistribution of the load will have been initiated. However, since the bar was not

initially designed to work within this load range, it is expected that the corresponding structural member would be replaced.

By providing sufficient glass fiber reinforcement, it is possible to generate a significant apparent strain-hardening behavior, as shown in the previous example. This is important since: (1) strain-hardening will provide for the redistribution of the loads to other parts of a structure, (2) it will provide for controlled, large deformations to take place before collapse, and (3) even if some outer glass fibers are damaged, the remaining ones can still provide a resistance equal to or greater than the yield strength. For a grade 60 steel bar, the ultimate stress is approximately 50 percent greater than the yield stress. A similar ratio would be desirable for the hybrid composite.

MEDIUM-MODULUS HIGH-STRAIN CORE-SHELL HYBRIDS

An approximate cost in dollars per pound for the various fibers is indicated in Table 1. It is observed that construction of the formerly proposed hybrid is prohibitive. By choosing a lower modulus carbon fiber, such as T-300 or AS4C (Refs 23 and 46), costs can be significantly reduced at the expense of a lower hybrid modulus.

Assume an E-glass shell and an AS4C core hybrid with a resilient vinyl ester matrix as shown in Table 1. This hybrid can offer an ultimate stress about 50 percent greater than its yield stress, as follows (assuming a total volume fiber $V_{gf} + V_{cf} = 60$ percent):

$$\sigma_u = 1.5 \, \sigma_y$$

$$\sigma_{ug} V_{gf} + E_m \epsilon_{ug} V_m = 1.5 \, (\sigma_{uc} V_{cf} + E_{gf} \epsilon_{uc} V_{gf} + E_m \epsilon_{uc} V_m)$$

$$500 V_{gf} + 460(0.048)0.4 = 1.5 \, (560 V_{cf} + 10500(0.016) V_{gf} + 460(0.016)0.4)$$

from which

$$V_{cf} = 0.14 \text{ and } V_{gf} = 0.46$$

Assume $V_{cf} = 0.15$ and $V_{gf} = 0.45$, and the area of the hybrid composite distributed accordingly among the core and the shell, i.e., $A_{core} = 1/3 \, A_{shell} = 1/4 \, A_{total}$.

For this hybrid, the yield stress would be 163 ksi, the ultimate stress 230 ksi, and the initial stiffness 9,860 ksi, about one-third that of steel.

FINITE ELEMENT ANALYSIS OF CORE-SHELL HYBRID

To determine the effects of the glass fiber orientation, a finite element analysis was carried out. A three-dimensional slice of a 3/4-inch-diameter rebar was discretized using low order three-dimensional solid elements, as shown in Figure 3. The two outer layers represent the glass fiber composite (i.e., glass fibers in a resin matrix), whereas the inner layers represent the carbon fiber composite. Carbon fibers were always oriented along the bar axis, whereas the glass fiber orientation was varied (angle α on Figure 3). Both composites were modeled using an orthotropic material model, whose axes were oriented accordingly. The loading was applied

5

via controlled displacement of one of the faces, while the other face was kept within a plane. Both faces were free to displace radial'y but axial rotations were prevented.

Two finite element programs, ADINA (Ref 47) and ABAQUS (Ref 48), were used with the same discretization of the rebar section. A small strain formulation was employed in both cases. In the ABAQUS model the axes of orthotropy are allowed to rotate with the average material rotation at each material point. In the rebar specimen the axes of orthotropy vary with increasing axial and radial deformation. For example, an axial expansion combined with a radial contraction could produce a deformation state in which the fibers would mostly rotate and not be subjected to any significant extension along their axis. This geometrical nonlinearity effect is better captured if the local axes of orthotropy can rotate, although, for small deformations, the difference is small. The ABAQUS model was run once with and once without the NLGEOM option (within the *STEP procedure) which accounts for geometric nonlinearities.

In the rebar specimen modeled, all glass fibers were oriented at the same angle. In practice it may be easier to produce a constant pitch, which would result in a variable orientation depending on the radial distance of the fibers to the bar axis. In this case, the difference between model and specimen would increase with the thickness of the glass composite layer. The composite described in the previous example was used in the model, but with the glass fiber orientation (i.e., its angle with the rebar axis) incremented from 0 to 45 degrees. The matrix considered was a resilient vinyl ester resin as shown in Table 1.

Two analyses were carried out with each model. First, the bar was analyzed just prior to the rupture of the carbon fibers. This allowed for the determination of the yield properties. Second, the bar was analyzed at a bar strain of 4.8 percent (i.e., just prior to the rupture of the glass fibers when these are aligned axially). In this case, the core transverse properties were kept the same but the core composite axial modulus was reduced to the matrix modulus.

MATERIAL PROPERTIES

In the model, material properties were determined as follows. For the AS4C carbon composite core:

$$E_l = E_a = .6 E_{cf} + .4 E_m = .6 \times 33 + .4 \times .46 = 20.0 \text{ Msi}$$

$$E_t = E_b = E_c = 1.5 \text{ Msi}$$

$$\mu_l = \mu_{lt} = 0.25$$

$$\mu_{tl} = 0.01875$$

$$\mu_t = \mu_{tt} = 0.3$$

$$G_l = G_{ab} = G_{ac} = 950 \text{ ksi}$$

$$G_t = G_{bc} = E_t/2(1+\mu_t) = 577 \text{ ksi}$$

These properties (as well as those for the E-glass composite) were estimated from Table 2 and Ref 18, p. 178. The notation used in Reference 18 (page 186) was followed.

6

For the E-glass composite shell:

$$E_l = E_a = .6 \, E_{gf} + .4 \, E_m = .6 \times 10.5 + .4 \times .46 = 6.5 \text{ Msi}$$

$$E_t = E_b = E_c = 1.8 \text{ Msi}$$

$$\mu_l = \mu_{lt} = 0.28$$

$$\mu_{tl} = 0.0775$$

$$\mu_t = \mu_{tt} = 0.3$$

$$G_l = G_{ab} = G_{ac} = 800 \text{ ksi}$$

$$G_t = G_{bc} = E_t/2(1+\mu_t) = 692 \text{ ksi}$$

where

E_a, E_b, E_c = orthotropic moduli in directions a (axial), b, and c (radial)

E_l, E_t = orthotropic moduli in longitudinal and transverse directions

$$\mu_{lt} = -\frac{\epsilon_t}{\epsilon_l} = \text{Poisson ratio (due to a longitudinal stress)}$$

$$\mu_{tl} = -\frac{\epsilon_l}{\epsilon_t} = \text{Poisson ratio (due to a transverse stress)}$$

$$= \mu_{lt} \frac{E_t}{E_l}$$

G_{ij} = shear modulus

Note that for a uniaxial transversely isotropic composite, only five of the properties are independent (Ref 18, p. 186, and Ref 38).

Values for the longitudinal modulus of elasticity were found using the rule of mixtures. Values for the transverse modulus of elasticity can be found if the fibers' transverse properties are known (Refs 49, 50, and 51).

MODEL CONSTRAINTS ON POISSON'S RATIOS

In the finite element application, the orthotropic stress-strain constitutive matrix is forced to be symmetric by setting

$$\mu_{tl} = \mu_{lt} \frac{E_t}{E_l}$$

Since for unidirectional composites $\mu_{tl} < \mu_{lt}$ the error is small and allows for the use of a symmetric solver.

In addition, the orthotropic stress-strain constitutive matrix is symmetric and has to be positive definite (Ref 47). As a consequence the following relationships must hold (Ref 47):

$$\mu_{ji} < (E_i/E_j)^{0.5}$$

$$\mu_{ab}\mu_{bc}\mu_{ac}\frac{E_a}{E_c} < 0.5\,(1 - \mu^2_{ab}\frac{E_a}{E_b} - \mu^2_{bc}\frac{E_b}{E_c} - \mu^2_{ac}\frac{E_a}{E_c}) < 0.5$$

For a transversely isotropic material, this reduces to the two following inequality constraints:

$$\mu_{tl} < (E_t/E_l)^{0.5}$$

$$\mu_{tt}\mu^2_{tl}\frac{E_l}{E_t} < 0.5\,(1 - 2\mu^2_{tl}\frac{E_l}{E_t} - \mu^2_{tt}) < 0.5$$

The second constraint shows that the value for μ_{tt} has a much smaller weight than the value for μ_{tl} (i.e., variations of μ_{tt} will not significantly affect the limit for μ_{tl}). For the glass composite then, assuming $\mu_{tt} = 0.3$, these constraints yield:

$$\mu_{tl} < 0.526 \text{ and } \mu_{tl} < 0.311$$

both of which are verified. For the carbon composite (given also $\mu_{tt} = 0.3$), the requirements are:

$$\mu_{tl} < 0.273 \text{ and } \mu_{tl} < 0.162$$

both of which are also verified.

8

EFFECTS OF FIBER ORIENTATION

Bar Modulus

For the case of small strains and small displacements, results from both programs were practically equal (within 4 significant digits) and are shown in Figure 4 as SMALL STRAINS. When all fibers were oriented axially (0-degree angle), the numerical analyses yielded a moduli of 9,825 ksi very close to the expected 9,860 ksi. The third simulation including geometric nonlinearity effects (NLGEOM) yielded 9,707 ksi. Prior to the rupture of the core carbon fibers, it is shown that the equivalent bar modulus E decreased from about 10,000 ksi to about 7,000 ksi with increasing inclination of the glass fibers (Figure 4).

Prior to the rupture of the shell glass fibers, the bar modulus was only dependent on the glass composite and is denoted Eg (Figure 5). Eg decreased with increasing inclination angle.

Bar Stresses

For the bar pseudo-yield stress (i.e., the bar stress just prior to the rupture of the carbon fibers, Figure 4), differences between numerical and analytical results were due to the fact that the first ones calculated ultimate stresses as $E\epsilon_u$ and the second ones as σ_u. The bar pseudo-yield stress varied from about 157 to 109 ksi with increasing angle (at 0 degree, 163 ksi were expected).

The bar stress at a bar strain of 4.8 percent is shown in Figure 5 as Sg. At this point only the glass composite is carrying significant longitudinal stresses.

Glass Fibers Strain

With respect to the effect on the glass fibers strain, Figure 6 shows that at an angle of 37.5 degrees, the glass fibers are strained only about 50 percent of the bar strain. This implies that the ultimate hybrid bar strain could reach values similar to the ultimate strain in steel bars. This high failure strain would result in extensive concrete cracking which could serve as an indicator of potential collapse as with steel rebars.

CONCLUSIONS

It is possible to engineer hybrid FRP reinforcing bars which would offer high initial stiffness, pseudo-ductility and hardening, and high strains to failure. The high initial stiffness ensures lower deflections and better concrete contribution. The pseudo-ductility and hardening allow for the redistribution of forces and prevention of sudden structural collapse. The high strain to failure serves as a precursor to failure. The properties of these hybrid FRP bars can be very similar to those of the steel bars they are meant to replace.

ACKNOWLEDGMENT

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Table 1
Material Properties

Material	Tensile Modulus (Msi)	Ultimate Stress at 72 Degrees (ksi)	Ultimate Strain (%)	Reference	Cost ($/lb)
E-Glass	10.5	500	4.8	18, p 46 20	0.8
S-Glass	12.5	665	5.7	18, p 107 21	6
P-100 (carbon)	100-110	350	0.32	18, p 113 23	800
P-120 (carbon)	120.	325	0.27	18, p 361 23	850
Leadline K13B2U/4U (carbon)	120.	570	0.48	24	-
AS4C (carbon)	33.0	560	1.60	46	12
T-300 (carbon)	33.5	530	1.4	23	23
Vinyl ester (resin)	0.52	12	4.0	18, p 91 26	-
Resilient vinyl ester (Derakane)	0.46	11	10.0	26, p 274 34	-

14

Table 2
Typical Properties of Unidirectional Epoxy Composite
with 60 Percent Fiber Volume

| Property	S-2 Glass	E Glass	AS4C Carbon
Longitudinal Modulus of Elasticity - E_l (Msi)	8.1	6.5	20.0
Transverse Modulus of Elasticity - E_t (Msi)	2.6	1.8	1.5
Axial Shear Modulus - G_l (Msi)	1.1	0.8	0.95
Longitudinal Poisson Ratio - μ_l	0.27	0.28	0.25
Longitudinal Tensile Strength - σ_{ult} (ksi)	260	150	310
Longitudinal Compressive Strength - σ_{ulc} (ksi)	140	90	260
Transverse Tensile Strength - σ_{utt} (ksi)	9	7	9.5
Transverse Compressive Strength - σ_{utc} (ksi)	22	20	-
In-Plane Shear Strength - τ_{ul} (ksi)	16	10	-
Interlaminar Shear Strength - τ_{uli} (ksi)	12	10	18
Longitudinal Flexural Strength - σ_{ulf} (ksi)	215	..	260
Longitudinal Bearing Strength - σ_{ulb} (ksi)	74	-	-
Ultimate Longitudinal Tensile Strain - ϵ_{ul} (%)	3.1	2.3	1.6
Ultimate Long. Compressive Strain - ϵ_{ul} (%)	1.45	1.4	-
Ultimate Transverse Tensile Strain - ϵ_{ul} (%)	0.38	0.4	0.7
Ultimate Trans. Compressive Strain - ϵ_{ul} (%)	1.55	1.1	-
Ultimate In-plane Shear Strain - δ_{uli} (%)	2.05	-	-
Fiber Density - d (lb/in^3)	0.072	0.075	0.064
References	21	20	46
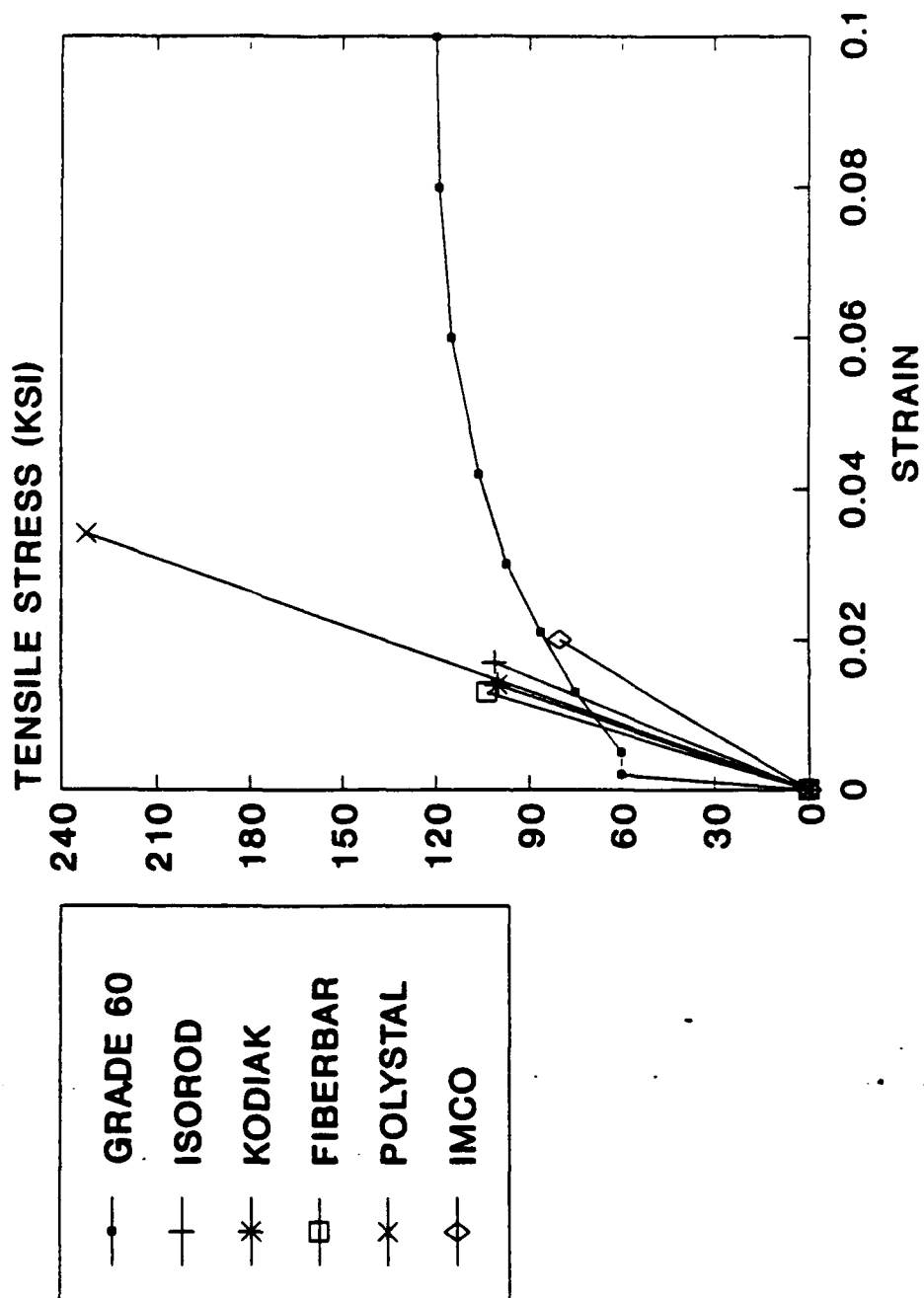
Figure 1
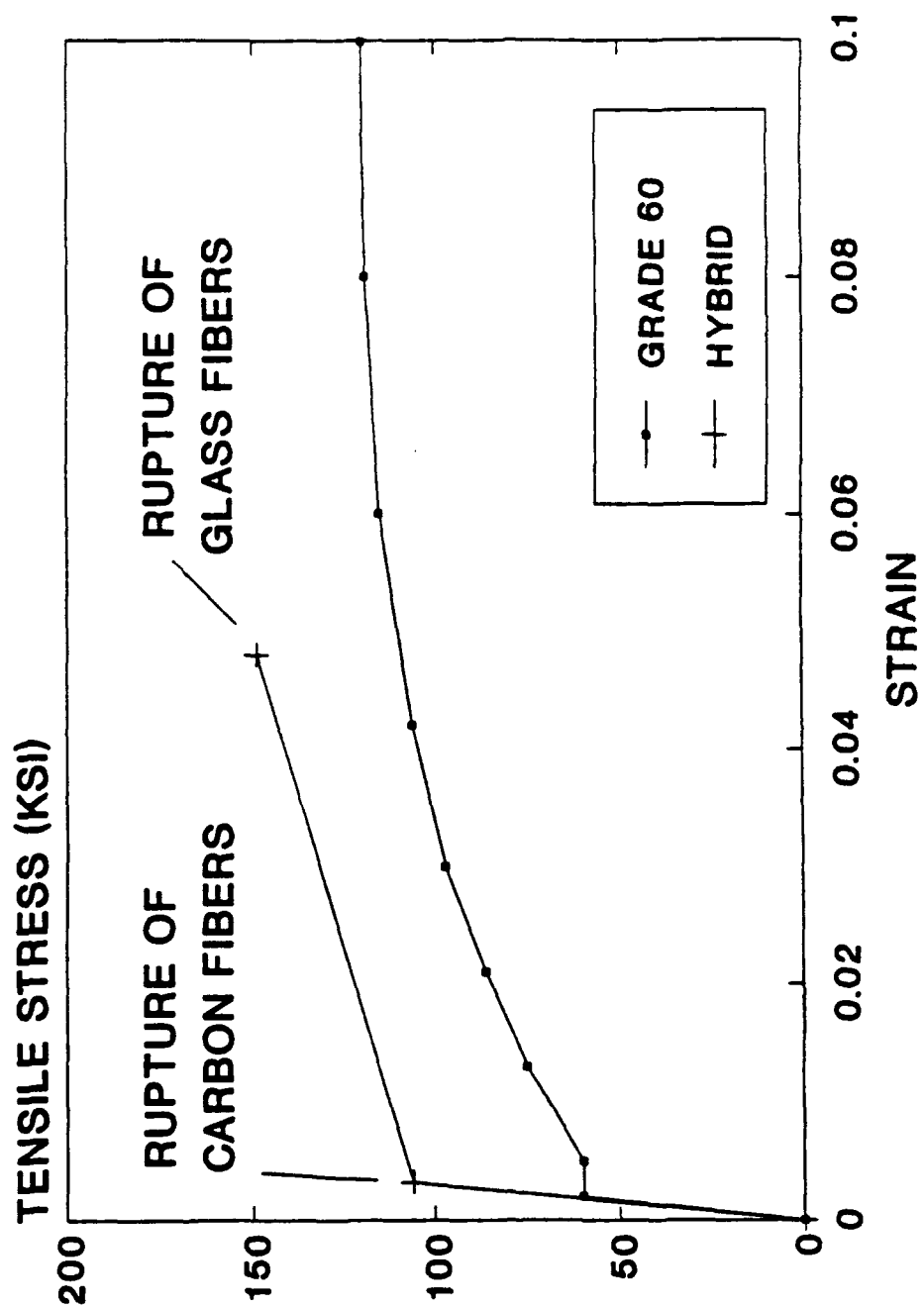Relative ductility and stiffness of FRP rebars.

16

Figure 2
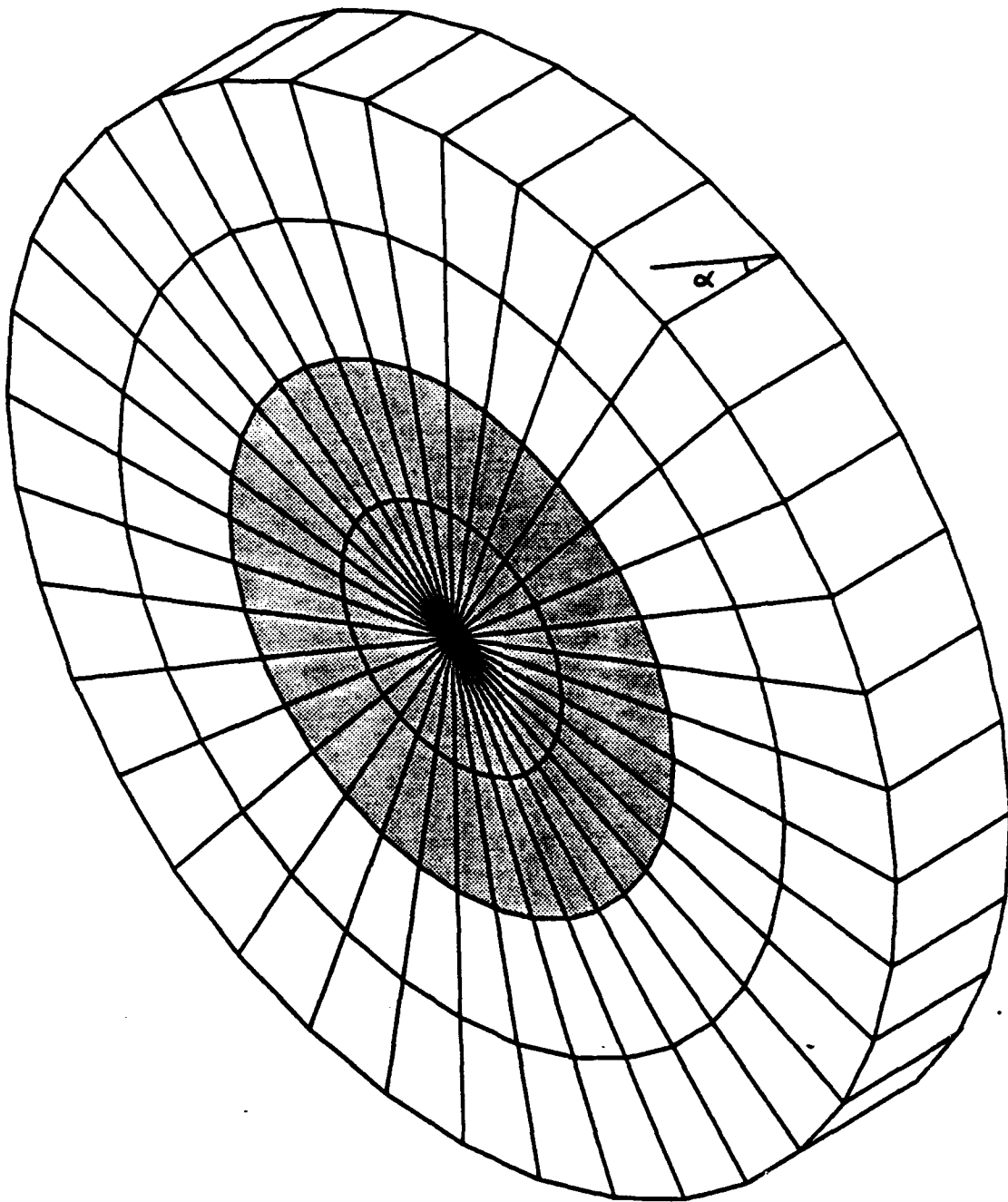Relative ductility and stiffness of hybrid FRP rebar.

Figure 3
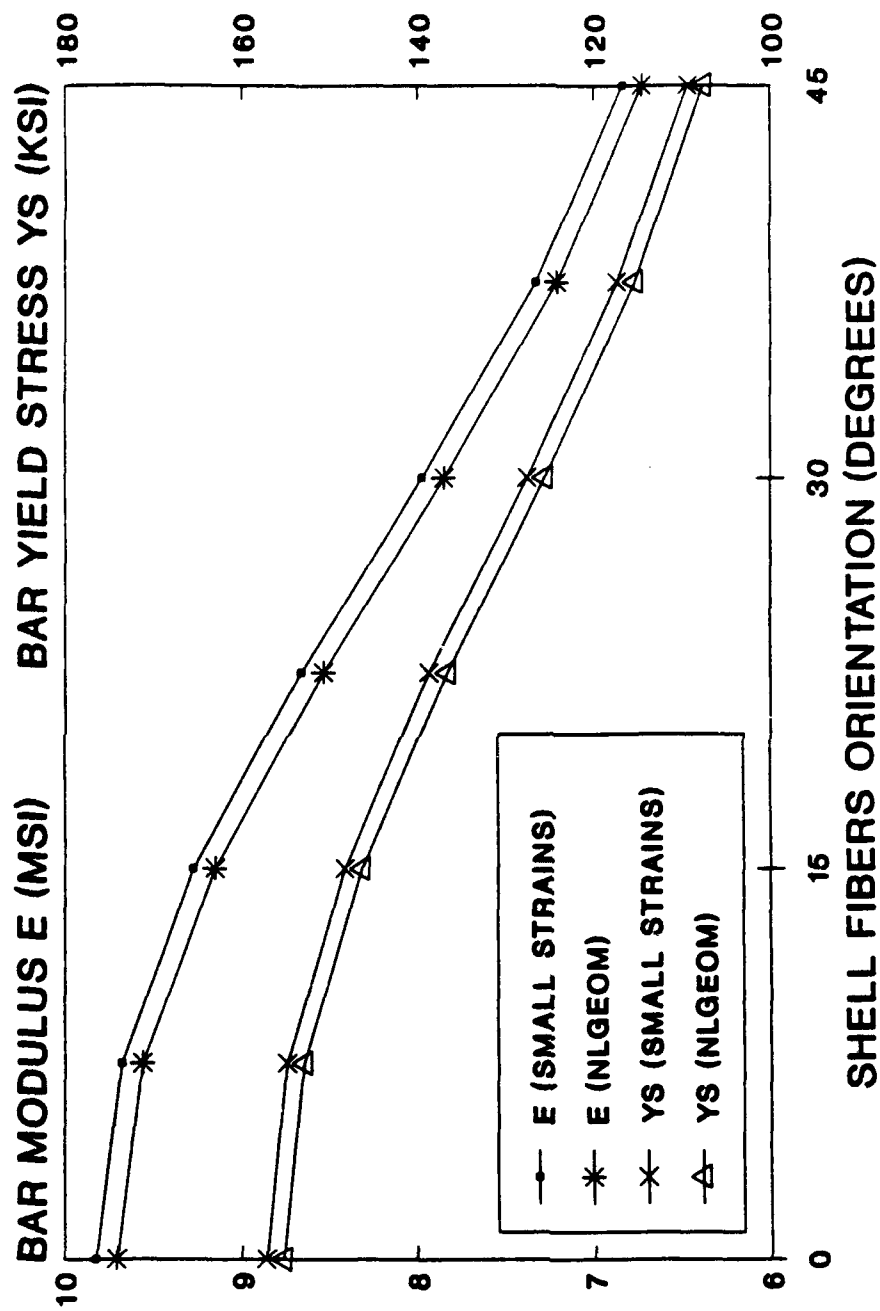Section of core-shell hybrid composite.

18

Figure 4
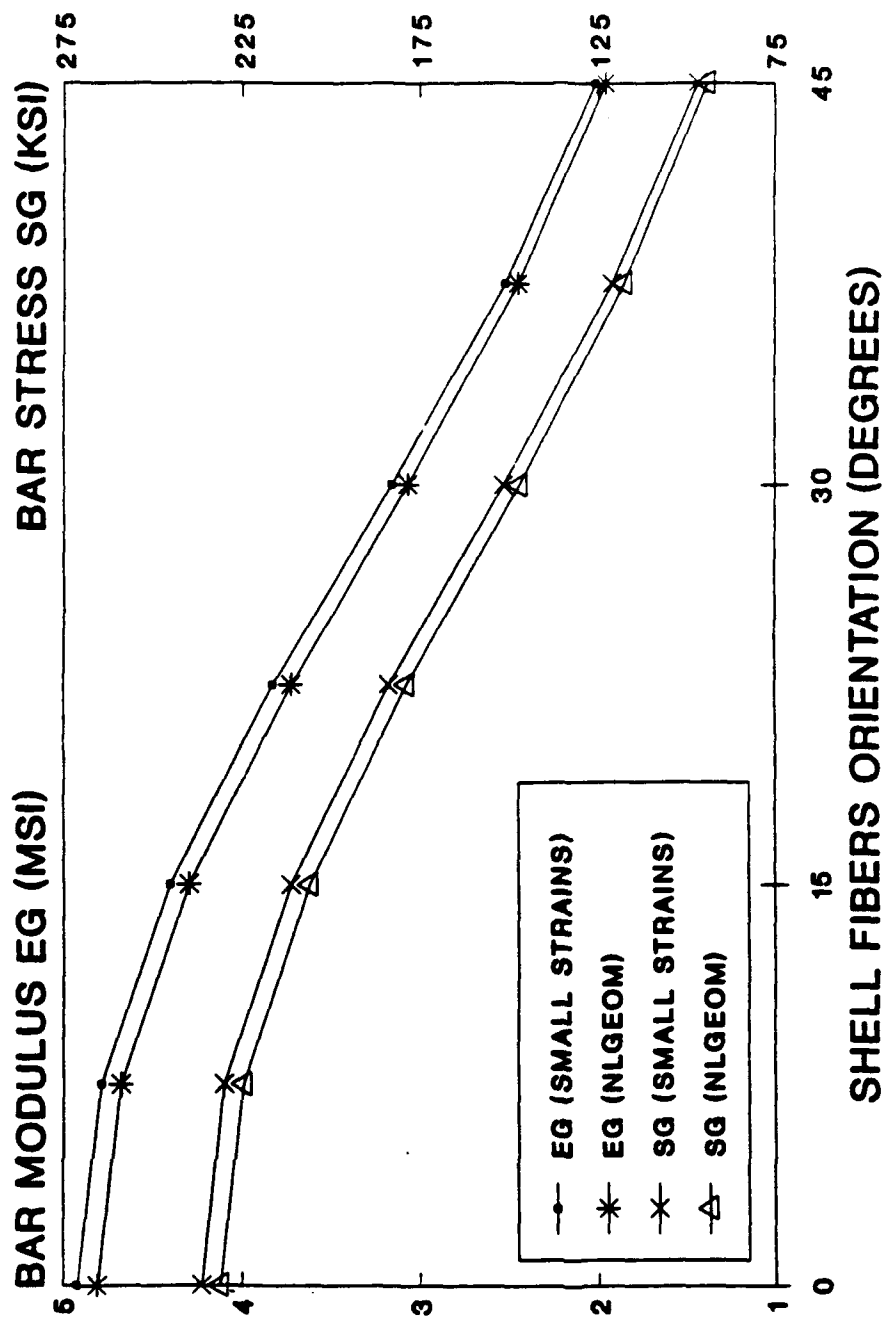Hybrid core-shell properties at carbon fiber fracture.

Figure 5
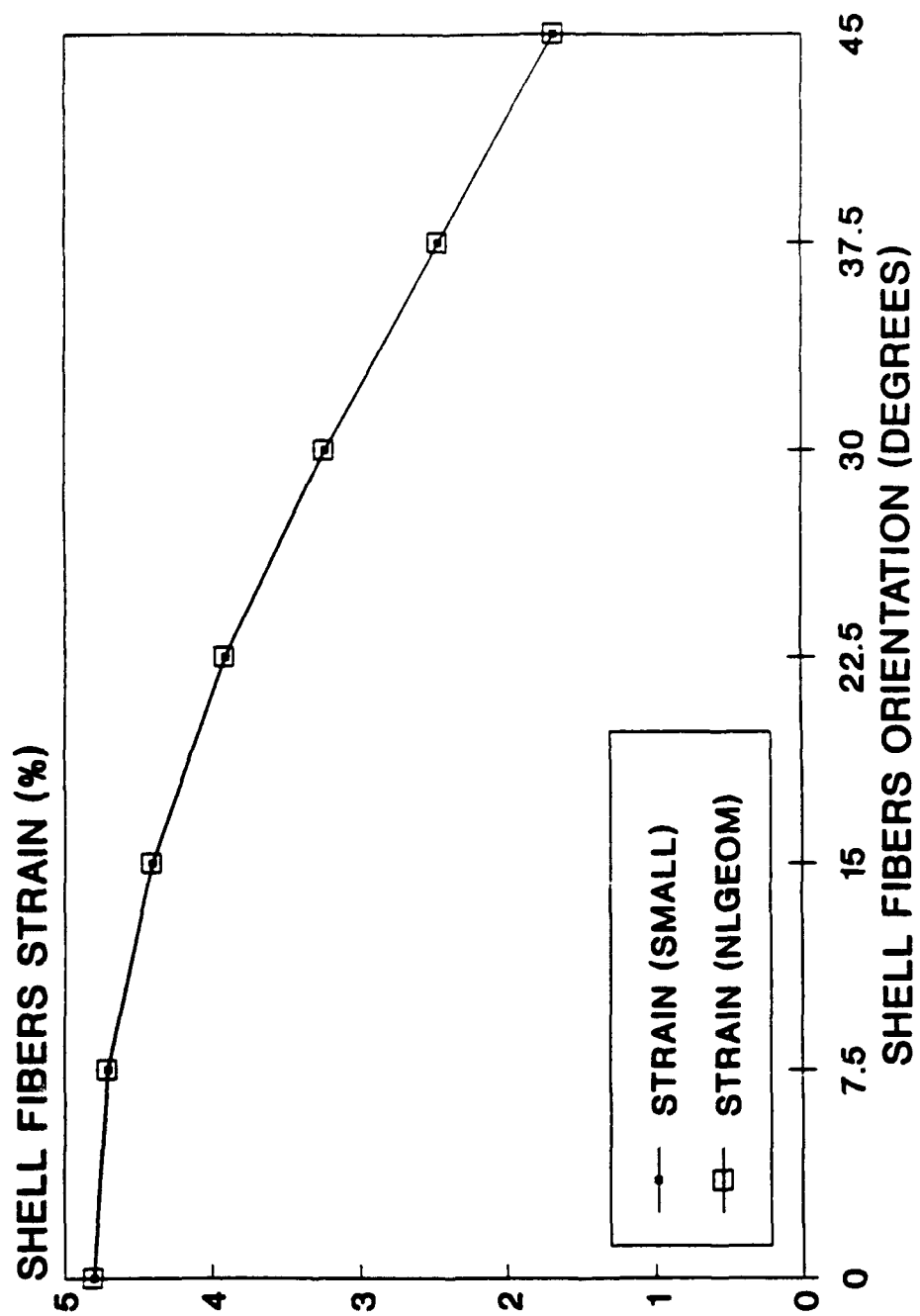Hybrid core-shell properties at 4.8 percent bar strain.

Figure 6
Shell fibers strain at 4.8 percent bar strain.

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